

1 MODULATORS FOR RESONANT OPTICAL POWER
2 CONTROL DEVICES AND METHODS OF FABRICATION
3 AND USE THEREOF

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8 FIELD OF THE INVENTION

9 The field of the present invention relates to devices for modulating optical power
10 transmission through optical fiber. In particular, apparatus, methods of use, and methods of
11 fabrication of resonant optical power control devices are described herein for modulating optical
12 power transmission through a fiber-optic waveguide using a modulator element coupled to a
13 whispering-gallery-mode optical resonator in turn coupled to the fiber-optic waveguide.

14 BACKGROUND

15 This application is related to subject matter disclosed in:

- 16 A1) U.S. provisional Application No. 60/111,484 entitled "An all-fiber-optic modulator" filed
17 12/07/1998 in the names of Kerry J. Vahala and Amnon Yariv, said provisional
18 application being hereby incorporated by reference in its entirety as if fully set forth
19 herein;
- 20 A2) U.S. Application No. 09/454,719 entitled "Resonant optical wave power control devices
21 and methods" filed 12/07/1999 in the names of Kerry J. Vahala and Amnon Yariv, said
22 application being hereby incorporated by reference in its entirety as if fully set forth
23 herein;
- 24 A3) U.S. provisional Application No. 60/108,358 entitled "Dual tapered fiber-microsphere
25 coupler" filed 11/13/1998 in the names of Kerry J. Vahala and Ming Cai, said provisional
26 application being hereby incorporated by reference in its entirety as if fully set forth
27 herein;
- 28 A4) U.S. Application No. 09/440,311 entitled "Resonator fiber bi-directional coupler" filed
29 11/12/1999 in the names of Kerry J. Vahala, Ming Cai, and Guido Hunziker, said

1 application being hereby incorporated by reference in its entirety as if fully set forth
2 herein; and

3 A5) U.S. provisional Application No. 60/183,499 entitled "Resonant optical power control
4 devices and methods of fabrication thereof" filed 02/17/2000 in the names of Peter C.
5 Sercel and Kerry J. Vahala, said provisional application being hereby incorporated by
6 reference in its entirety as if fully set forth herein.

7 A6) U.S. provisional application entitled "Fiber-optic waveguides for evanescent optical
8 coupling and methods of fabrication and use thereof", filed 08/18/2000 in the names of
9 Peter C. Sercel, Guido Hunziker, and Robert B. Lee, Application No. 60/226,147, said
10 provisional application being hereby incorporated by reference in its entirety as if fully
11 set forth herein.

12 A7) U.S. provisional application entitled "Waveguides and resonators for integrated optical
13 devices and methods of fabrication and use thereof", filed concurrently with the present
14 application in the name of Oskar J. Painter, Application No. not yet assigned, said
15 provisional application being hereby incorporated by reference as if fully set forth herein.

16 A8) U.S. provisional Application No. 60/170,074 entitled "Optical routing/switching based on
17 control of waveguide-ring resonator coupling", filed 12/09/1999 in the name of Amnon
18 Yariv, said provisional application being hereby incorporated by reference in its entirety
19 as if fully set forth herein.

20 A9) U. S. Pat. No. 6,052,495 entitled "Resonator modulators and wavelength routing
21 switches" issued 04/18/2000 in the names of Brent E. Little, James S. Foresi, and
22 Hermann A. Haus, said patent being hereby incorporated by reference in its entirety as if
23 fully set forth herein.

24 A10) U. S. Pat. No. 6,101,300 entitled "High efficiency channel drop filter with absorption
25 induced on/off switching and modulation" issued 08/08/2000 in the names of Shanhui
26 Fan, Pierre R. Villeneuve, John D. Joannopoulos, Brent E. Little, and Hermann A. Haus,
27 said patent being hereby incorporated by reference in its entirety as if fully set forth
28 herein.

1 This application is also related to subject matter disclosed in the following 31 publications, each
2 of said 31 publications being hereby incorporated by reference in its entirety as if fully set forth
3 herein:

- 4 P1) Ming Cai, Guido Hunziker, and Kerry Vahala, "Fiber-optic add-drop device based on a
5 silica microsphere whispering gallery mode system", IEEE Photonics Technology Letters
6 Vol. 11 686 (1999);
- 7 P2) J. C. Knight, G. Cheung, F. Jacques, and T. A. Birks, "Phased-matched excitation of
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- 10 P3) R. D. Pechstedt, P. St. J. Russell, T. A. Birks, and F. D. Lloyd-Lucas, "Selective coupling
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- 13 P4) R. D. Pechstedt, P. St. J. Russell, "Narrow-band in-line fiber filter using surface-guided
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- 15 P15) Ming Cai, Oskar Painter, and Kerry J. Vahala, "Observation of critical coupling in a fiber
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10 Optical fiber and propagation of high-data-rate optical pulse trains therethrough has
11 become the technology of choice for high speed telecommunications. Wavelength division
12 multiplexing (WDM) techniques are now commonly used to independently transmit a plurality
13 of signals over a single optical fiber, independent data streams being carried by optical modes
14 propagating through the optical fiber at a slightly differing optical carrier wavelengths. A
15 propagating mode of a particular wavelength must be modulated, independently of other
16 propagating wavelengths, in order to carry a signal. A signal carried by a particular wavelength
17 channel must be independently accessible for routing from a particular source to a particular
18 destination. These requirements have previously required complex and difficult-to-manufacture
19 modulating and switching devices requiring extensive active alignment procedures during
20 fabrication/assembly, and as a result are quite expensive. Such devices may require conversion
21 of the optical signals to electronic signals and/or vice versa, which is quite power consuming and
22 inefficient. In the patent applications A1 through A6 cited above a new approach has been
23 disclosed for controlling optical power transmitted through an optical fiber that relies on the use
24 of resonant whispering-gallery-mode (hereinafter "WGM") optical resonators, or other optical
25 resonators, for direct optical coupling to a propagating mode of an optical fiber resonant with the
26 optical resonator, thereby enabling wavelength-specific modulation of optical signals
27 propagating through the optical fiber. A thorough discussion of the features and advantages of
28 such optical power control devices and techniques, as well as methods of fabrication, may be
29 found in these applications, already incorporated by reference herein.

1 A primary design goal of fiber optic communications has been that, to the greatest extent
2 feasible, components and/or devices should keep the light wave signal in optical fiber. This is
3 based on the common sense observation that to couple light from a device into optical fiber or
4 vice versa is very expensive to implement and typically introduces undesirable loss. Fiber Bragg
5 filters and erbium fiber optical amplifiers are technologies that exemplify successful realizations
6 of the goal. Other examples more directly relevant to this disclosure are optical power control
7 devices, including all-fiber-optic modulators and/or all-fiber channel add-drop filters (described
8 in the patent applications A1 through A8 cited hereinabove and incorporated by reference
9 herein). One important element of these latter devices is optical coupling between a fiber-optic
10 waveguide and a whispering-gallery-mode optical resonator. The WGM optical resonator
11 provides wavelength specificity, since only propagating optical modes substantially resonant
12 with the WGM optical resonator will be significantly affected by the device. A fiber-optic
13 waveguide for transmitting the optical signal through the control device is typically provided
14 with an evanescent optical coupling segment, where an evanescent portion of the propagating
15 optical mode extends beyond the waveguide and overlaps a portion of a whispering-gallery
16 optical mode of the WGM optical resonator, thereby optically coupling the WGM optical
17 resonator and the fiber-optic waveguide. The evanescent optical coupling segment may take one
18 of several forms, including an optical fiber taper, D-shaped optical fiber, an optical fiber with a
19 saddle-shaped concavity in the cladding layer, and/or other functionally equivalent
20 configurations. These are discussed in detail in patent applications A1 through A6 cited herein.

21 The WGM optical resonator structure may comprise a glass micro-sphere or micro-disk,
22 a fiber-ring resonator, a semi-conductor ring/waveguide, or other functionally equivalent
23 structure, described in detail in earlier-cited applications A1 through A6. A high-Q WGM
24 optical resonator supports relatively narrow-linewidth resonant whispering-gallery optical modes
25 (i.e., having a linewidth consistent with typical linewidths of a WDM system, TDM system, or
26 other optical data transmission system), which in an optical power control device may optically
27 couple to propagating optical modes of the fiber-optic waveguide of substantially resonant
28 optical wavelength. The WGM optical resonator therefore provides the wavelength selectivity of
29 the optical power control device. Once coupled into the WGM optical resonator, dissipation of
30 the optical signal may be modulated to in turn modulate the level of transmission of the

1 propagating optical mode through the fiber-optic waveguide (and hence through the optical power
2 control device), as described in the earlier-cited patent applications A1 through A6. By
3 controllably adjusting the loss per round trip experienced by the whispering-gallery optical mode
4 circulating within the WGM optical resonator, the optical power control device may function in
5 either of two modes:

6 1) Switching the WGM optical resonator between an over-coupled condition (where the
7 loss per round trip in the WGM optical resonator is small compared to the optical coupling
8 between the fiber-optic waveguide and WGM optical resonator, and the transmission through the
9 fiber-optic waveguide past the resonator is large) and the condition of critical coupling (at which
10 the optical coupling of the fiber-optic waveguide and WGM optical resonator is substantially
11 equal to the round trip loss of the WGM optical resonator, and substantially all of the optical
12 power is dissipated by/from the WGM optical resonator resulting in near zero optical
13 transmission through the fiber-optic waveguide past the WGM optical resonator); or

14 2) Switching states between the condition of critical coupling (near zero transmission
15 through the fiber-optic waveguide) and a condition of under-coupling (where the loss per round
16 trip in the WGM optical resonator is large compared to the optical coupling between the fiber-
17 optic waveguide and WGM optical resonator, and the transmission through the fiber-optic
18 waveguide past the WGM optical resonator is non-zero).

19 For all of these modes of operation, there are essentially two classes of mechanism by
20 which one can introduce round trip loss to a circulating optical wave (i.e., resonant whispering-
21 gallery optical mode) in the WGM resonator. Either optical power of the circulating wave can
22 be absorbed, or it can be gated out of the WGM optical resonator into a second optical element,
23 such as a second waveguide or second resonator. The gating may preferably be achieved by
24 control of the optical coupling between the WGM optical resonator and the second optical
25 element and functions rather like a trapdoor. These two general possibilities are both disclosed
26 in earlier-cited applications A1, A2, A5, and A6. The current disclosure describes such devices
27 in greater detail, particularly optical loss transducers or elements provided as a separate element
28 to control optical loss from a WGM resonator by either of these means (as distinguished from
29 designs in which the loss control element is an integral part of the WGM optical resonator
30 structure).

SUMMARY

Certain aspects of the present invention may overcome one or more aforementioned drawbacks of the previous art and/or advance the state-of-the-art of optical power control devices and fabrication and use thereof, and in addition may meet one or more of the following objects:

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein a modulator optical element evanescently optically coupled to a WGM optical resonator provides a controlled level of WGM resonator round-trip optical loss, enabling controlled modulation of a level of transmission of a propagating optical mode through a transmission fiber-optic waveguide (evanescently optically coupled to the WGM optical resonator) when the propagating optical mode is substantially resonant with the whispering-gallery optical mode;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the modulator optical element comprises an open optical waveguide (i.e., a modulator optical waveguide);

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the modulator optical element comprises a closed optical waveguide (i.e., a modulator optical resonator);

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the WGM resonator round-trip optical loss may be controlled by controlling optical absorption of the modulator optical element;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the WGM resonator round-trip optical loss may be controlled by controlling optical power transfer from the optical resonator to the modulator optical element;

To provide a resonant optical power control device, and methods for fabricating and using the same, wherein the WGM resonator round-trip optical loss may be

1 controlled by controlling a resonant optical frequency of the modulator optical
2 resonator;

3 To provide a resonant optical power control device, and methods for fabricating and
4 using the same, wherein the modulator optical element comprises an electro-
5 absorptive material, and application of a control electric field thereto controls the
6 optical absorption of the modulator optical element;

7 To provide a resonant optical power control device, and methods for fabricating and
8 using the same, wherein the modulator optical element comprises a multi-layer
9 distributed Bragg reflector (DBR) stack and an electro-absorptive material, and
10 application of a control electric field thereto controls the optical absorption of the
11 modulator optical element;

12 To provide a resonant optical power control device, and methods for fabricating and
13 using the same, wherein the modulator optical element comprises an electro-
14 refractive or electro-optic material, and application of a control electric field
15 thereto controls the optical power transfer from the WGM resonator to the
16 modulator optical element;

17 To provide a resonant optical power control device, and methods for fabricating and
18 using the same, wherein the modulator optical element comprises a multi-layer
19 distributed Bragg reflector (DBR) stack and an electro-refractive or electro-optic
20 material, and application of a control electric field thereto controls the optical
21 power transfer from the WGM resonator to the modulator optical element;

22 To provide a resonant optical power control device, and methods for fabricating and
23 using the same, wherein the modulator optical resonator comprises an electro-
24 refractive or electro-optic material, and application of a control electric field
25 thereto controls the resonance optical frequency of the modulator optical
26 resonator;

27 To provide a resonant optical power control device, and methods for fabricating and
28 using the same, wherein the transmission fiber-optic waveguide, the WGM optical

1 resonator, and the modulator optical element, may be reproducibly, reliably, and
2 stably positioned and secured within the device;

3 To provide a resonant optical power control device, and methods for fabricating and
4 using the same, wherein the transmission fiber-optic waveguide, the WGM optical
5 resonator, and the modulator optical element are positioned by and secured to an
6 alignment device; and

7 To provide a resonant optical power control device, and methods for fabricating and
8 using the same, wherein the alignment device comprises first and second
9 alignment substrates, the transmission fiber-optic waveguide is positioned and
10 secured within an alignment groove on the first alignment substrate, the
11 modulator optical element is secured to the second alignment substrate, the WGM
12 resonator may be positioned and secured on the first or the second substrate, and
13 the assembled alignment device suitably positions the modulator optical element,
14 WGM resonator, and transmission fiber-optic waveguide relative to each other.

15 One or more of the foregoing objects may be achieved in the present invention by an
16 optical power control device comprising: a) a transmission fiber-optic waveguide; b) a WGM
17 optical resonator; c) a modulator optical element; and d) a modulator control element. The
18 transmission fiber-optic waveguide supports a propagating optical mode (wherein flows the
19 optical power to be controlled by the device) and is provided with an evanescent optical coupling
20 segment where an evanescent portion of the propagating optical mode extends beyond a surface
21 of the transmission fiber-optic waveguide. The whispering-gallery-mode (WGM) optical
22 resonator is positioned relative to the transmission fiber-optic waveguide so that a portion of a
23 whispering-gallery optical mode supported by the resonator at least partially spatially overlaps
24 the evanescent portion of the propagating optical mode. The transmission fiber-optic waveguide
25 and WGM optical resonator are thereby evanescently optically coupled. The modulator optical
26 element is positioned so that an evanescent portion of the WG optical mode at least partially
27 spatially overlaps the modulator optical element, thereby evanescently optically coupling the
28 WGM optical resonator and the modulator optical element. The modulator control element is
29 operatively coupled to the modulator optical element for modulating, in response to an applied
30 control signal, i) a level of optical power transfer through evanescent optical coupling of the

1 whispering-gallery-mode optical resonator and the modulator optical element, ii) a level of
2 optical loss (absorption or scattering) of the modulator optical element, and/or iii) a resonant
3 frequency of the modulator optical element, thereby enabling controlled modulation of the
4 round-trip optical loss of the WGM resonator, in turn enabling controlled modulation of a level
5 of transmission of the propagating optical mode through the transmission fiber-optic waveguide
6 when the propagating optical mode is substantially resonant with the whispering-gallery optical
7 mode.

8 The modulator optical element may comprise an open optical waveguide or a closed
9 optical waveguide (i.e., a modulator optical resonator). The modulator optical element may
10 comprise an electro-absorptive material, so that application of a control electric field thereto
11 control the optical absorption of the modulator optical element. The modulator optical element
12 may comprise an electro-refractive or electro-optic material, so that application of a control
13 electric field thereto controls optical power transfer from the WGM resonator into the modulator
14 optical element. The modulator optical element may comprise a distributed Bragg reflector
15 (DBR) stack and an electro-refractive or electro-optic material, so that application of a control
16 electric field thereto controls optical power transfer from the WGM resonator into the modulator
17 optical element. A modulator optical resonator may comprise an electro-refractive or electro-
18 optic material (and may include a DBR stack), so that application of a control electric field
19 thereto controls resonance optical frequency of the modulator optical resonator.

20 The transmission optical waveguide, the WGM optical resonator, and the modulator
21 optical element may be reproducibly, reliably, and stably positioned and secured within the
22 optical power control device using an alignment device. The alignment device comprises first
23 and second alignment substrates, the transmission fiber-optic waveguide is positioned and
24 secured within an alignment groove on the first alignment substrate, the modulator optical
25 element is secured to the second alignment substrate, the WGM resonator may be positioned and
26 secured on the first or the second substrate, and the assembled alignment device suitably
27 positions the modulator optical element, WGM resonator, and transmission fiber-optic
28 waveguide relative to each other.

29 Additional objects and advantages of the present invention may become apparent upon
30 referring to the preferred and alternative embodiments of the present invention as illustrated in
31 the drawings and described in the following written description and/or claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows an optical power control device according to the present invention.

Figs. 2A and 2B show side and partial sectional views, respectively, of an optical power control device according to the present invention.

Figs. 3A and 3B show partial sectional views of an optical power control device according to the present invention.

Figs. 4A and 4B show side and end views, respectively, of an optical power control device according to the present invention.

Figs. 5A, 5B, 5C, 5D, and 5E are schematic diagrams of optical power control devices according to the present invention.

Figs. 6A, 6B, and 6C show end, side, and cross-sectional views, respectively, of an optical power control device according to the present invention.

Fig. 7 shows a side view of an optical power control device according to the present invention.

Figs. 8A and 8B show side and top views, respectively, of an optical power control device according to the present invention.

Fig. 9 is a flow diagram for fabricating a modulator optical element according to the present invention.

Fig. 10 is a process diagram for fabricating a modulator optical element according to the present invention.

Fig. 11 is a process diagram for fabricating a modulator optical element according to the present invention.

Fig. 12 is a process diagram for fabricating a modulator optical element according to the present invention.

Fig. 13 is a process diagram for fabricating a modulator optical element according to the present invention.

1 Fig. 14 is a process diagram for fabricating a modulator optical element according to the present
2 invention.

3 Fig. 15 is a flow diagram for fabricating a modulator optical element according to the present
4 invention.

5 Fig. 16 is a process diagram for fabricating a modulator optical element according to the present
6 invention.

7 Figs. 17A, 17B, and 17C are two partial sectional views and one top view, respectively, of an
8 optical power control device according to the present invention.

9 Figs. 18A, 18B, and 18C are two partial sectional views and one top view, respectively, of an
10 optical power control device according to the present invention.

11 Figs. 19A and 19B are partial sectional views of an optical power control device according to the
12 present invention.

13 Figs. 20A and 20B are partial sectional views of an optical power control device according to the
14 present invention.

15 Figs. 21A and 21B are partial sectional views of an optical power control device according to the
16 present invention.

17 Figs. 22A and 22B are partial sectional views of an optical power control device according to the
18 present invention.

19 Figs. 23A and 23B are partial sectional views of an optical power control device according to the
20 present invention.

21 It should be noted that the relative proportions of various structures shown in the Figures may be
22 distorted to more clearly illustrate the present invention. In particular, the size differential
23 and resonator thickness of fiber-rings may be greatly exaggerated relative to the underlying
24 optical fiber diameter in various Figures for clarity. Various metal, semiconductor, and/or
25 other thin films, layers, and/or coatings may also be shown having disproportionate and/or
26 exaggerated thicknesses for clarity. Relative dimensions of various waveguides, resonators,
27 optical fibers/tapers, and so forth may also be distorted, both relative to each other as well as

1 transverse/longitudinal proportions. For example, several Figures showing a lateral view of a
2 fiber-taper show the length of fiber over which the taper occurs much shorter than is actually
3 the case. The text and incorporated references should be relied on for the appropriate
4 dimensions of structures shown herein.

5 It should be noted that most of the Figures may each may depict one of several distinct
6 embodiments of an optical power control device according to the present invention. Each
7 set of embodiments corresponding to a particular Figure are similar in spatial arrangement,
8 but differ in functional details that are not represented in the Figures. In particular, loss-
9 modulated, index-modulated, resonance-modulated, interference-modulated embodiments
10 may appear substantially similar in the Figures. The particular functional aspects of the
11 different embodiments are described in different text sections that each refer to one or more
12 common Figures.

DETAILED DESCRIPTION OF PREFERRED AND ALTERNATIVE EMBODIMENTS

For purposes of the present written description and/or claims, “whispering-gallery-mode optical resonator” (equivalently, WGM optical resonator, WGM resonator, WGMOR, WGMR) shall denote a resonator structure capable of supporting a substantially resonant whispering-gallery optical mode, the whispering-gallery optical mode typically having an evanescent portion extending beyond the whispering-gallery-mode optical resonator. Such resonator structures may include, but are not limited to, spheres, near-spheres, oblate and/or prolate spheroids, ellipsoids, ovals, ovoids, racetracks, polygons, polyhedra, cylinders, disks, rings, micro-spheres, micro-disks, micro-rings, fiber-rings, disks and/or rings on substrates (including structures disclosed in earlier-cited application A7), ring or other closed waveguides, and/or functional equivalents thereof. In particular, the various WGM optical resonator structures as disclosed in earlier-cited application A5 (denoted collectively as “fiber-rings”) are particularly noted for inclusion as WGM resonators for purposes of this disclosure. However, other resonator structures may be equivalently employed without departing from inventive concepts disclose and/or claimed herein. Any resonator having an evanescent portion of a resonant optical mode or that may otherwise be “evanescently optically coupled” to another optical element (see definition hereinbelow) may be employed as the resonant optical resonator element of the present invention (i.e., the element that confers wavelength specificity on the optical power control device). Optical resonator structures disclosed in earlier-cited application A7 (denoted collectively as “DBR rings”) are particularly noted for inclusion as optical resonators suitable for use in the present invention. Although the term “WGM optical resonator” is used throughout the remainder of the present disclosure, it should be understood that any optical resonator that may be evanescently optically coupled to a transmission waveguide and to a modulator optical element as disclosed herein shall be considered functionally equivalent to a WGM optical resonator.

For purposes of the present written description and/or claims, “transmission fiber-optic waveguide” (equivalently, transmission waveguide, transmission fiber-optic, transmission optical fiber, TFOWG, TWG) shall denote an optical fiber (polarization-maintaining or otherwise) provided with a evanescent optical coupling segment where an evanescent portion of a

1 propagating optical mode may extend beyond the fiber-optic waveguide and overlap a portion of
2 some other optical mode, thereby enabling evanescent optical coupling between the transmission
3 optical waveguide and another optical element. Such a transmission optical waveguide may
4 comprise an optical fiber taper, a D-shaped optical fiber, an optical fiber with a saddle-shaped
5 concavity in the cladding layer, an optical fiber with a side-polished flattened portion, and/or
6 functional equivalents. Such transmission optical waveguides are described in further detail in
7 earlier-cited applications A1 through A6. Such transmission fiber-optic waveguides typically
8 serve to facilitate insertion of optical power control devices according to the present invention
9 into an optical power transmission system.

10 For purposes of the written description and/or claims, "evanescent optical coupling" shall
11 generally denote those situations in which two optical elements, each capable of supporting a
12 propagating and/or resonant optical mode and at least one having an evanescent portion
13 extending beyond its respective optical element, are optically coupled by at least partial spatial
14 overlap of the evanescent portion of one optical mode with at least a portion of the other optical
15 mode. The amount, strength, level, or degree of optical power transfer from one optical element
16 to the other through such evanescent optical coupling depends on the spatial extent of the overlap
17 (both transverse and longitudinal), the spectral properties of the respective optical modes, and the
18 relative spatial phase matching of the respective optical modes (also referred to as modal index
19 matching). To transfer optical power most efficiently, the respective modal indices of the optical
20 modes (equivalently, the respective modal propagation constants), each in its respective optical
21 element, must be substantially equal. Mismatch between these modal indices decreases the
22 amount of optical power transferred by evanescent coupling between the optical elements, since
23 the coupled modes get further out of phase with each other as each propagates within its
24 respective optical element and the direction of the optical power transfer eventually reverses
25 itself. The propagation distance over which the modes interact (i.e., the effective interaction
26 length) and the degree of index matching (or mis-matching) together influence the overall flow
27 of optical power between the coupled modes. Optical power transfer between the coupled modes
28 oscillates with a characteristic amplitude and spatial period as the modes propagate, each in its
29 respective optical element. Neglecting the effects of optical loss in the optical elements, the
30 optical power transfer amplitude is determined primarily by the phase mismatch (substantially

complete optical power transfer with little phase mismatch; decreasing optical power transfer with increasing phase mismatch). The optical power transfer spatial period is determined by the degrees of transverse spatial overlap and phase mismatch (shorter spatial period for greater overlap; shorter spatial period for larger phase mismatch). By controlling the phase mismatch and/or transverse spatial overlap, these characteristics may be exploited for controlling optical power transfer between optical elements. For example, by altering the phase mismatch, a device may be switched from a first condition, in which a certain fraction of optical power is transferred from a first optical mode in a first optical element to a second optical mode in a second optical element (phase mismatch set so that the effective interaction length is about half of the characteristic spatial period described above), to a second condition in which little or no optical power is transferred (phase mismatch set so that the effective interaction length is about equal to the characteristic spatial period). Further discussion of optical coupling may be found in Fundamentals of Photonics by B. E. A. Saleh and M. C. Teich (Wiley, New York, 1991), hereby incorporated by reference in its entirety as if fully set forth herein. Particular attention is called to Chapters 7 and 18.

It should be noted that optical power control devices, their fabrication, and their use according to the present invention are intended primarily for modulating a propagating optical mode having a wavelength between about 0.8 μm and about 1.7 μm (the wavelength range typically utilized for fiber-optic telecommunications). However, these devices, methods of fabrication, and methods of use may be adapted for use at any desired wavelength while remaining within the scope of inventive concepts disclosed and/or claimed herein.

A typical optical power control device according to the present invention is shown schematically in Fig. 1. In subsequent Figures, specific embodiments for transmission optical waveguide 110, whispering-gallery-mode resonator 120, and/or alignment structures therefor may be shown. These are illustrative and exemplary, and should not be construed as limiting the scope of the present invention as shown, described, and/or claimed except when specifically recited in a particular claim. Transmission waveguide 110 is typically an optical fiber taper, although a side etched optical fiber (as in earlier-cited application A6) is also shown, and any other transmission waveguide having a suitable evanescent coupling segment may be equivalently employed. WGM resonator 120 is typically shown as fiber-ring resonator (as in

earlier-cited application A5), although any other optical resonator suitable for evanescent optical coupling to a transmission waveguide and a modulator optical element may be equivalently employed. A propagating optical mode enters an input end 112 of transmission fiber-optic waveguide 110, and exits an output end 114 of transmission waveguide 110. Transmission waveguide 110 is provided with an evanescent optical coupling segment 116 where an evanescent portion of the propagating optical mode may extend beyond the transmission waveguide 110. Evanescent optical coupling segment 116 may comprise a tapered segment of a fiber taper transmission optical waveguide (as described, for example, in earlier-cited applications A1 through A5), a saddle- or pit-shaped evanescent coupling portion of a cladding layer surface of a fiber-optic waveguide (as described in earlier-cited application A6), or other functionally equivalent structure. A whispering-gallery-mode optical resonator 120 supports a substantially resonant whispering-gallery optical mode, having an evanescent portion extending beyond the whispering-gallery-mode optical resonator. The WGM optical resonator 120 is positioned relative to the evanescent coupling segment of the transmission waveguide 110 so that the evanescent portion of the propagating optical mode at least partially spatially overlaps a portion of the whispering-gallery optical mode, thereby evanescently optically coupling the WGM resonator 120 and the transmission waveguide 110. The WGM optical resonator 120 provides the wavelength selectivity of control device. Unless the propagating optical mode is substantially resonant with a whispering-gallery resonant optical mode of the WGM resonator 120, optical coupling of the propagating optical mode into and/or circulation of its radiation within the WGM resonator 120 is/are negligible, and the propagating optical mode is transmitted through the transmission waveguide 110 substantially unaffected by the presence of WGM resonator 120 or the operational state of control device. (Hence the phrase “resonant optical power control device”.)

In contrast, when the propagating optical mode is substantially resonant with a whispering-gallery resonant optical mode of WGM resonator 120, optical coupling of the propagating optical mode into and circulation of its radiation within WGM optical resonator 120 may be quite substantial. For a relatively high-Q WGM optical resonator (on the order of 10^6 may be achieved; 10^4 - 10^5 typically employed in devices according to the present invention), the level of circulating optical power in the whispering-gallery optical mode may reach a level many

1 times higher than the power level of the propagating optical mode. Slight changes in the optical
2 loss per round trip for this circulating radiation dramatically affects the level of transmission of
3 the propagating optical mode through the transmission waveguide 110. By controllably
4 adjusting this optical loss per round trip, resonant optical power control device may function in
5 either of two modes:

6 1) Switching the optical loss between i) an over-coupled condition (where the optical
7 loss per round trip in the WGM optical resonator 120 is small compared to the optical coupling
8 between the transmission waveguide 110 and WGM optical resonator 120) in which the
9 transmission of the propagating optical mode through transmission waveguide 110 past the
10 WGM resonator is large, and ii) a condition of critical coupling (where the optical loss per
11 round trip in the WGM optical resonator 120 is substantially equal to optical coupling of
12 transmission waveguide 110 and WGM optical resonator 120) in which substantially all of the
13 optical power is dissipated by/from the WGM optical resonator resulting in near zero optical
14 transmission of the propagating optical mode through transmission waveguide 110 past WGM
15 optical resonator 120; or

16 2) Switching the optical loss between i) the condition of critical coupling with near zero
17 transmission through transmission waveguide 110, as described above, and ii) a condition of
18 under-coupling (where the optical loss per round trip in the WGM optical resonator 120 is large
19 compared to the optical coupling between the transmission waveguide 110 and WGM optical
20 resonator 120) in which the transmission of the propagating optical mode through transmission
21 waveguide 110 past WGM optical resonator 120 is non-zero.

22 For purposes of the present written description and/or claims, it shall be assumed (unless
23 specifically stated otherwise) that the propagating optical mode (whose optical power
24 transmission through the transmission fiber-optic waveguide is to be controlled by device) is
25 substantially resonant with the whispering-gallery resonant optical mode (supported by the
26 WGM optical resonator).

27 A modulator optical element 130 is positioned relative to WGM optical resonator 120 so
28 that an evanescent portion of the whispering-gallery optical mode at least partially spatially
29 overlaps at least a portion of an optical mode of modulator optical element 130. Modulator

1 optical element 130 is thereby evanescently optically coupled to WGM optical resonator 120.
2 Modulator optical element 130 serves to enable controlled adjustment of the round trip optical
3 loss of WGM optical resonator 120 between over-, critical-, and/or under-coupled conditions in
4 one of several of ways: i) modulator optical element 130 may provide a controlled level of direct
5 optical loss of the whispering-gallery optical mode (collectively referred to herein as “loss-
6 modulated” or more specifically “absorption-modulated” devices); ii) a level of evanescent
7 optical coupling between WGM optical resonator 120 and modulator optical element 130 may be
8 controlled, with radiation coupled from WGM resonator 120 into modulator optical element 130
9 absorbed within, transmitted away from, and/or otherwise dissipated from the modulator optical
10 element 130 (collectively referred to herein as “coupling-modulated” or more specifically
11 “index-modulated” devices); iii) a resonant frequency of a resonant modulator optical element
12 130 may be controlled, so that modulator optical element only provides loss for the whispering-
13 gallery optical mode when one of the modulator resonance frequencies substantially coincides
14 with the whispering-gallery mode frequency (collectively referred to herein as “resonance-
15 modulated” devices); and iv) a modulator optical element 130 may be evanescently optically
16 coupled to the WGM resonator 120 at two separate points and the modulator modal index may
17 be controlled, enabling interferometric control of the round-trip loss of WGM resonator 120
18 (collectively referred to herein as “interference-modulated” devices). Modulator control
19 element(s) 170 is/are operatively coupled to the modulator optical element 130 for enabling
20 control of the round trip loss of the WGM resonator 120 by application of a control signal, in
21 turn enabling controlled modulation of transmission of the propagating optical mode through the
22 transmission waveguide 110.

23 In a first group of embodiments of the present invention, a level of direct optical loss of
24 the whispering-gallery optical mode by the modulator optical element is controlled to enable
25 controlled modulation of transmission of the propagating optical mode through the transmission
26 waveguide. The modulator optical element in these so-called “loss-modulated” or “absorption-
27 modulated” embodiments may comprise an open optical waveguide structure (in which an
28 optical mode of the waveguide does not follow a closed path and re-circulate and/or resonate
29 within the waveguide; referred to hereinafter as a “modulator waveguide”), or may comprise an
30 ring, resonator (including a second whispering-gallery-mode optical resonator), or other closed

1 optical waveguide structure (in which an optical mode of the waveguide may re-circulate and/or
2 resonate; referred to collectively hereinafter as a “modulator resonator”). In either case, the
3 modulator optical element is positioned so that an evanescent portion of the whispering-gallery
4 optical mode at least partially spatially overlaps an optical mode of the modulator optical
5 element. A modulator optical element incorporating material whose optical absorption, at the
6 wavelength of the whispering-gallery optical mode, can be controlled thereby enables control of
7 the round trip optical loss experienced by the whispering-gallery optical mode in the WGM
8 resonator, in turn achieving the desired goal of controlled modulation of transmission of the
9 propagating optical mode through the transmission waveguide as described above.

10 Absorption-modulated embodiments of an optical power control device according to the
11 present invention are shown in Figs. 2A, 2B, 3A, and 3B in which the modulator optical element
12 comprises an open modulator optical waveguide positioned tangentially with respect to the
13 WGM optical resonator. Transmission waveguide 110 is shown as a fiber-optic taper. A fiber-
14 optic waveguide having an evanescent coupling portion of the cladding layer surface as
15 described in detail in earlier-cited application A6, or other fiber-optic waveguide having an
16 evanescent coupling portion could be equivalently employed. WGM optical resonator 120 is
17 shown in Figs. 2A, 2B, 3A, and 3B as a fiber-ring resonator as described in detail in earlier-cited
18 application A5. Other WGM resonator structures could be equivalently employed, including but
19 not limited to a rings, spheres or near-spheres, disks, microspheres, microdisks, or other
20 resonator geometry as recited hereinabove. In Figs. 2A and 2B, the modulator optical element is
21 a slab waveguide 132 in substantial tangential engagement with WGM resonator 120, either in
22 direct mechanical contact, or positioned at a specific distance from the WGM resonator to yield a
23 desired level of evanescent optical coupling.

24 An evanescent portion of the whispering-gallery optical mode supported by WGM
25 resonator 120 extends radially beyond the circumference thereof, and therefore spatially overlaps
26 a portion of an optical mode of the slab waveguide 132. Absorption-modulated slab waveguide
27 132 may preferably be fabricated incorporating a material having an optical loss (typically
28 optical absorption), at the wavelength of the whispering-gallery optical mode, which may be
29 controlled by a modulator control element. The optical absorption per unit length in the
30 interaction region is preferably sufficiently large to enable the WGM resonator round trip optical

the slab and WGM resonator might be well phase-matched and the optical loss of the slab chosen to produce a critical-coupling condition at the fiber-optic waveguide/resonator junction, while the optical absorption of the slab may be switched to a higher level to yield an under-coupled condition at the fiber-optic waveguide/resonator junction. Many other schemes and combinations of phase match/mismatch and operative levels of optical absorption of the slab waveguide may be employed while remaining within the scope of inventive concepts disclosed and/or claimed herein. For a given WGM optical resonator geometry, slab waveguide material, and so forth, some experimentation is typically required to determine the level of evanescent coupling, and the appropriate levels of slab waveguide optical loss to produce the desired modulation of the WGM resonator round trip loss.

In Figs. 3A and 3B, the modulator optical element is an absorption-modulated two-dimensional (2D) waveguide 134 on a substrate 136 and positioned tangentially with respect to WGM optical resonator 120. Many of the same considerations applicable to the absorption-modulated slab waveguide embodiment of Figs. 2A and 2B apply to the absorption-controlled 2D waveguide embodiment of Figs. 3A and 3B. The 2D waveguide 134 may preferably be fabricated incorporating a material having an optical absorption at the wavelength of the whispering-gallery optical mode that may be controlled by a modulator control element, and which may produce WGM resonator round trip loss sufficient to achieve critical coupling. Modal index mismatch between the 2D waveguide and the WGM optical resonator must be controlled in the manner described hereinabove for the absorption-controlled slab waveguide. In addition to the 2D waveguide material and the substrate material, the transverse geometry of the 2D waveguide must also be chosen to yield the desired spatial overlap and phase match/mismatch properties.

The optical absorption of absorption-modulated slab waveguide 132 or 2D waveguide 134 may be controlled by electronic, optical, and/or other means. For example, a quantum well, multi-quantum well (MQW), other semi-conductor, or other functionally equivalent material may be incorporated into the modulator waveguide as an electro-absorptive material, wherein the optical absorption of the modulator waveguide may be altered by application of a control field. A modulator control element may comprise control electrodes suitably positioned to apply the control electric field. Alternatively, the optical absorption by such materials may

1 controlled by injection of current into the material. The presence of additional charge carriers
2 (electrons and/or holes, as the case may be) may serve to increase or decrease the optical
3 absorption of the waveguide material, depending on the bandgap, band structure, and/or doping
4 of the electro-absorptive material and the wavelength of the optical mode to be modulated.
5 Control electrodes or other electrical contacts may serve to inject a control electrical current.
6 Optical excitation of such materials may also serve to generate charge carriers, thereby enabling
7 control of the waveguide optical absorption by application of an optical control signal. Other
8 classes of materials exhibiting photo-bleaching, excited state absorption, saturable absorption,
9 and/or non-linear optical absorption may be equivalently incorporated into the modulator
10 waveguide to enable control of the waveguide optical absorption by application of an optical
11 control signal.

12 A preferred material for fabricating slab waveguide 132 and/or 2D waveguide 134
13 comprises a multi-quantum well (MQW) material comprising alternating layers of i) quantum
14 well layers of a material having a bulk bandgap close to or only slightly larger (within about 10
15 meV to 30 meV, for example) than the photon energy of the whispering-gallery optical mode,
16 and ii) barrier layers having a bandgap substantially larger than the photon energy of the
17 propagating optical mode. The bandgaps referred to here are not the bulk bandgaps for the
18 various materials, but the bandgaps of the materials as incorporated as individual layers of a
19 multi-layer structures described. The MQW material is surrounded by a pair of contact layers
20 (doped or otherwise) for facilitating electrical contact to the control electrodes. Delta-doping of
21 the contact layers may be preferred, to minimize unwanted diffusion of dopant(s) into the MQW
22 material. The control signal comprises a control voltage applied across the electrodes, thereby
23 applying a control electric field substantially normal to the layers of the MQW material. This
24 electric field may red-shift resonance(s) of the MQW material with respect to the frequency of
25 the whispering-gallery optical mode through a quantum-confined Stark effect (QCSE), a Franz-
26 Keldysh effect (FKE), a quantum-confined Franz-Keldysh effect (QCFKE), or other similar
27 mechanism. Typically, the electro-absorptive MQW material would be chosen having a
28 resonance i) slightly above the photon energy of the whispering-gallery optical mode in the
29 absence of a control electric field, and ii) slightly below the photon energy of the whispering-
30 gallery optical mode when red-shifted by application of the control electric field. In this way

1 application of the control signal alters the optical loss experienced by the whispering-gallery
2 optical mode, in turn altering the transmission level of the propagating optical mode through the
3 transmission waveguide.

4 In an exemplary embodiment for controlling wavelengths typically used for long-haul
5 fiber-optic telecommunications (between about 1.2 μm and about 1.7 μm), the quantum well
6 layers, barrier layers, and doped contact layers may comprise InGaAsP, the quantum well layers
7 may be between about 7 nm thick and about 15 nm thick with a bulk bandgap between about 1.3
8 μm and about 1.6 μm , the barrier layers may be between about 20 nm thick and about 50 nm
9 thick with a bulk bandgap between about 1.0 μm and about 1.4 μm , and the doped contact layers
10 may be between about 20 nm thick and about 100 nm thick. In a preferred embodiment, the
11 quantum well layers may be about 10 nm thick with a bulk bandgap of about 1.6 μm , the barrier
12 layers may be about 20 nm thick with a bandgap of about 1.2 μm , and the delta-doped contact
13 layers may be about 50 nm thick. Many such MQW materials are readily available
14 commercially, and may be specified by layer thickness, layer bandgap, and layer composition.
15 The bulk bandgap of a particular layer material may be generally well-known and determined by
16 the precise composition/stoichiometry of the material, while the layer bandgap may often be
17 determined in a well-known manner from a combination of layer composition/stoichiometry,
18 layer thickness, and/or structural strain induced by adjacent layers. Many material combinations
19 (extant or hereafter developed), layer thicknesses, and bandgaps may be employed for
20 modulating many other optical wavelengths without departing from inventive concepts disclosed
21 and/or claimed herein. Several alternative material combinations are disclosed in earlier-cited
22 application A7.

23 An absorption-modulated embodiment of an optical power control device according to
24 the present invention is shown in Figs. 4A and 4B in which the modulator optical element
25 comprises an open arcuate modulator optical waveguide 138 positioned axially with respect to
26 the WGM optical resonator. Transmission waveguide 110 is shown as a fiber-optic taper. A
27 fiber-optic waveguide having a saddle-shaped evanescent coupling portion, as described in detail
28 in earlier-cited application A6, or other fiber-optic waveguide could be equivalently employed.
29 WGM optical resonator 120 is shown as a fiber-ring resonator as described in detail in earlier-
30 cited application A5. Other optical resonator structures could be equivalently employed. In Fig.

1 4A spacer 139 is shown for positioning arcuate waveguide 138 at the proper distance from
2 WGM resonator 120. In this particular embodiment the spacer 139 comprises a portion of an
3 adjacent fiber segment connected to the fiber-ring resonator with arcuate waveguide 138
4 deposited thereon, bonded thereto, or otherwise held in contact therewith. Some experimentation
5 will typically be required to determine the spacing between WGM resonator 120 and arcuate
6 waveguide 138 that produces the desired level of round-trip optical loss for WGM resonator 120
7 and the appropriate phase matching conditions between WGM resonator 120 and arcuate
8 waveguide 138. Once the proper thickness of spacer 139 has been determined, it may be
9 reproducibly fabricated by cleaving, etching, machining, lithography, cylindrical lithography, or
10 other suitable processing of the adjacent fiber segment. A functionally equivalent spacer may be
11 employed for other types of optical resonator as well. The same types of materials used for the
12 absorption-modulated slab and 2D waveguides described hereinabove may be employed for
13 fabricating absorption-modulated arcuate waveguide 138. In particular, arcuate waveguide 138
14 may comprise the InGaAsP multi-quantum well material described hereinabove, with the
15 alternating quantum well and barrier layers and surrounding contact layers substantially parallel
16 to WGM resonator 120 and with the control electric field applied substantially perpendicular to
17 WGM resonator 120. An advantage of this embodiment is increased interaction length between
18 the whispering-gallery optical mode and the arcuate waveguide relative to the tangentially
19 positioned waveguides of Figs. 2A, 2B, 3A, and 3B, therefore requiring smaller optical loss per
20 unit distance to achieve the same round trip optical loss in the WGM resonator.

21 A significant property of both tangentially- and axially-positioned absorption-modulated
22 open modulator optical waveguide structures is that since no re-circulation of any waveguide
23 optical mode occurs, the presence of the modulator optical waveguide has a substantially
24 negligible effect on the wavelength-dependent properties and/or resonant behavior of the
25 adjacent WGM optical resonator. Such wavelength/frequency shifting behavior can adversely
26 affect the performance of an optical power control device according to the present invention, or
27 alternatively may be exploited to enhance said performance, depending on the design,
28 construction, and use of a particular device.

29 Various absorption-modulated embodiments of an optical power control device according
30 to the present invention are shown schematically in Figs. 5A through 5E in which the modulator

1 optical element comprises a closed optical waveguide (i.e., a modulator optical resonator 140)
2 positioned tangentially (Figs. 5A and 5B) or axially (Figs. 5C, 5D, and 5E) with respect to the
3 WGM resonator 120, and oriented substantially parallel to (Figs. 5A, 5C, and 5D) or
4 substantially perpendicular to (Figs. 5B and 5E) the WGM resonator 120. Transmission
5 waveguide 110 is shown (in cross-section) as a tapered fiber-optic waveguide. A fiber-optic
6 waveguide having a saddle-shaped evanescent coupling portion, as described in detail in earlier-
7 cited application A6, or other fiber-optic waveguide could be equivalently employed. WGM
8 optical resonator is shown generically as a micro-disk or micro-ring resonator. Other optical
9 resonator structures, such as the fiber-rings of earlier-cited application A5, could be equivalently
10 employed. Absorption-modulated modulator optical resonator 140 may comprise any of the
11 resonator structures recited earlier for WGM resonator 120, including but not limited to spheres,
12 near-spheres, oblate and/or prolate spheroids, ellipsoids, ovals, ovoids, racetracks, polygons,
13 polyhedra, cylinders, disks, rings, micro-spheres, micro-disks, micro-rings, fiber-rings, disks
14 and/or rings on substrates (including structures disclosed in earlier-cited application A7), ring or
15 other closed waveguides, and/or functional equivalents thereof, and are shown generically as
16 micro-disks or micro-rings in Figs. 5A through 5E. Absorption-modulated modulator optical
17 resonator 140 is shown in Figs. 5A and 5B in substantial tangential engagement with WGM
18 optical resonator 120, either in direct mechanical contact, or positioned at a specific distance
19 from the WGM resonator (by a spacer or other suitable alignment structure) to yield a desired
20 level of evanescent optical coupling. An evanescent portion of the whispering-gallery optical
21 mode extending radially beyond WGM resonator 120 may overlap a portion of an optical mode
22 of modulator optical resonator 140, either a radially-extending portion thereof when substantially
23 parallel to WGM resonator 120 (Fig. 5A), or an axially-extending portion thereof when
24 substantially perpendicular to WGM resonator 120 (Fig. 5B). Absorption-modulated modulator
25 optical resonator 140 is shown in Figs. 5C, 5D, and 5E positioned axially with respect to WGM
26 optical resonator 120, either in direct mechanical contact, or positioned at a specific distance
27 from the WGM resonator (by a spacer or other suitable alignment structure) to yield a desired
28 level of evanescent optical coupling. An evanescent portion of the whispering-gallery optical
29 mode extending axially beyond WGM resonator 120 may overlap a portion of modulator optical
30 resonator 140, either an axially-extending portion thereof when substantially parallel to WGM

1 resonator 120 (Figs. 5C and 5D), or a radially-extending portion thereof when substantially
2 perpendicular to WGM resonator 120 (Fig. 5E).

3 Absorption-modulated modulator optical resonator 140 may preferably be fabricated
4 incorporating material having an optical loss (typically optical absorption), at the wavelength of
5 the whispering-gallery optical mode, that may be controlled by a modulator control element.
6 The modulator optical resonator 140 should preferably have a resonant optical mode having
7 substantially the same wavelength as the whispering-gallery optical mode of WGM resonator
8 120 (and hence the propagating optical mode to be controlled). This enables transfer of optical
9 power from the WGM resonator and build-up of optical power within the modulator optical
10 resonator, in turn enabling a relatively small optical loss per unit length in the modulator optical
11 resonator to produce sufficiently large round trip optical loss for the WGM resonator coupled
12 thereto. If the modulator optical resonator and WGM optical resonator are not resonant with
13 each other, in contrast, the situation becomes analogous to that described hereinabove for the
14 open modulator waveguide embodiments, with relatively large optical loss per unit length
15 required in the modulator optical resonator to generate sufficient round trip optical loss for the
16 WGM resonator. A complication encountered when implementing an embodiment that includes
17 an absorption-modulated modulator resonator arises from the unavoidable wavelength shift of
18 the resonant optical mode of the modulator resonator that occurs with a change in the optical loss
19 thereof. The WGM resonator and modulator optical resonator must be treated as a coupled-
20 cavity system, and shifts in the modulator resonance wavelength may perturb the resonances of
21 the coupled system. This effect must be properly accounted for in designing an optical power
22 control device incorporating a modulator optical resonator, or alternatively, the effect may be
23 exploited for designing optical power control devices with specific wavelength dependent
24 performance characteristics. This effect may be somewhat mitigated for an absorption-
25 modulated resonator modulator element, since the optical loss of such a modulator resonator
26 tends to reduce the finesse of the modulator resonator and increase the bandwidth of its
27 resonances, in turn decreasing the effect of the modulator resonances on the WGM resonances in
28 the coupled-cavity system. In short, loss- or absorption-modulated resonator or “closed
29 waveguide” modulator optical elements having relatively low finesse (less than about 10) may
30 behave substantially less “resonator-like” than the relatively high-finesse WGM resonator.

1 The optical absorption of modulator optical resonator 140 may be controlled by
2 electronic, optical, and/or other means in ways completely analogous to those recited for the
3 modulator waveguides hereinabove, and utilizing the same and/or functionally equivalent
4 materials for fabrication and the same and/or functionally equivalent modulator control elements.
5 For example, a quantum well, multi-quantum well (MQW), or other semi-conductor material
6 may be incorporated into the modulator optical resonator as an electro-absorptive material,
7 wherein the optical absorption may be altered by application of a control electric field. A
8 modulator control element may comprise control electrodes suitably positioned to apply the
9 control electric field. Materials described hereinabove (for modulator waveguides), such as an
10 InGaAsP MQW material controlled by a QCSE, FKE, QCFKE, or similar mechanism, are also
11 suitable for incorporation into modulator resonator 140. The optical absorption by such quantum
12 well, MQW, and other semi-conductor materials may alternatively be controlled by injection of
13 current into the material. The presence of additional charge carriers (electrons and/or holes, as
14 the case may be) may serve to increase or decrease the optical absorption of the waveguide
15 material, depending on the bandgap, band structure, and/or doping of the semiconductor and the
16 wavelength of the optical mode to be modulated. Control electrodes or other electrical contact
17 may serve to inject a control electrical current. Optical excitation of such materials may also
18 serve to generate carriers, thereby allowing control of the waveguide optical absorption to be
19 controlled by application of an optical control signal. Other classes of materials exhibiting
20 photo-bleaching, excited state absorption, saturable absorption, and/or non-linear optical
21 absorption may be equivalently incorporated into the modulator resonator to enable control of
22 the waveguide optical absorption by application of an optical control signal.

23 The interaction region (i.e., the volume of overlap between the evanescent portion of the
24 whispering-gallery optical mode and the modulator optical resonator) is typically limited in
25 spatial extent by the geometries of the embodiments of Figs. 5A, 5B, 5D, and 5E, limiting the
26 distance over which phase matching must be controlled. Significantly more stringent phase
27 matching constraints may arise for the embodiment of Fig. 5C, in which WGM resonator 120
28 and modulator resonator 140 are substantially coaxial, since the interaction region extends
29 entirely around the WGM resonator 120. The entire modulator 140 need not have controlled
30 optical loss. It may be desirable to leave the interaction region without absorption-controlled

1 material, so that altering the absorption of the modulator resonator does not affect the phase
2 matching condition in the interaction region.

3 For the embodiments of Figs. 5A through 5E, the relative positioning of WGM resonator
4 120 and modulator resonator 140 must be reliable, reproducible, and stable. For a given
5 combination of WGM resonator (material(s) and/or geometry) and modulator (material(s) and/or
6 geometry), some experimentation will be necessary to determine the relative position resulting in
7 the desired degree of evanescent optical coupling therebetween (based on the degree of spatial
8 overlap and relative phase matching). Once the proper relative positioning has been determined,
9 a mechanical spacer or other suitable alignment aid may be employed to enable reliable,
10 reproducible, and stable relative positioning of the WGM resonator and the modulator optical
11 resonator in an optical power control device according to the present invention. Such spacers
12 may comprise a member integrally formed with the WGM resonator, a member integrally
13 formed with the modulator optical resonator, or an independent member fabricated
14 independently of either resonator. Economies of fabrication and/or assembly of the optical
15 control device may be realized when the spacer is integrally formed with one or the other of
16 these resonators.

17 Figs. 6A, 6B, and 6C show an optical power control device wherein: fiber-optic
18 waveguide 110 comprises a fiber-optic taper (another type of fiber-optic waveguide, including a
19 fiber-optic waveguide having a saddle-shaped coupling surface, could be equivalently
20 employed); WGM optical resonator 120 comprises a fiber-ring resonator; and modulator
21 resonator 140 comprises a ring of MQW material (as described above or otherwise) deposited
22 on, bonded to, or otherwise held in contact with an adjacent fiber segment 141 connected to the
23 fiber-ring. This embodiment corresponds to the arrangement shown schematically in Fig. 5C.
24 The adjacent fiber segment 141 serves as a mechanical spacer for reliable, reproducible, and
25 stable positioning of modulator resonator 140 relative to the fiber-ring. Once the proper
26 thickness of the spacer (i.e., adjacent fiber segment 141) has been determined, it may be
27 reproducibly fabricated by cleaving, etching, machining, lithography, cylindrical lithography,
28 and/or other suitable processing of the adjacent fiber segment. Layers 172 and 174 may
29 comprise contact layers and/or electrodes for applying a control electric field to a modulator
30 resonator 140 comprising an electro-absorptive material as enumerated and disclosed

hereinabove. Fig. 7 shows a similar embodiment in which the fiber-ring is fabricated from PANDA-type polarization preserving optical fiber. One or more internal structural elements 142 of the PANDA fiber, protruding axially from fiber-ring WGM resonator 120, serve as the spacer for maintaining reliable, reproducible, and stable relative positioning of the fiber-ring WGM resonator and modulator resonator 140 (a micro-disk in this example, which may include contact/electrode layers not shown). Modulator resonator 140 may be bonded to or otherwise held in contact with structural elements 142. Structural elements 142 may preferably be left protruding from the fiber-ring by differential etching of the fiber-ring and the structural elements, or may result from any suitable machining, lithographic, or other processing technique for producing such structures.

A more elaborate embodiment of an optical power control device according to the present invention is shown in Figs. 8A and 8B. Fiber-optic waveguide 110 comprises a fiber-optic taper (another type of fiber-optic waveguide, including a fiber-optic waveguide having a saddle-shaped coupling surface, could be equivalently employed). WGM optical resonator 120 comprises a fiber-ring resonator. Modulator optical element 140 is fabricated on a semiconductor substrate and comprises a disk incorporating MQW material, and in this case may have a relatively low Q-factor (i.e., less resonator-like). Modulator element 140 nevertheless may provide a controlled level of optical loss for fiber-ring resonator around substantially the entire circumference of the fiber-ring resonator, enabling substantially full modulation of optical power transmitted through fiber taper 110 through relatively small changes in the absorption per unit length of modulator element 140. For wavelengths in the 1.2 μm to 1.7 μm range, a preferred substrate material is InP, while a preferred MQW material is an InGaAsP MQW layer 147 surrounded by delta-doped InGaAs contact layers 148 and 149, which enable application of control voltages via bottom electrode 178 (via delta-doped InGaAs layer 177 and doped InP spacer 179) and top ring electrode 176. An insulating layer 175 may also be provided. These materials have been described in detail hereinabove, and other suitable substrate and resonator materials may be equivalently employed. By depositing an appropriate sequence of epitaxial layers and suitably processing, modulator optical resonator 140 and associated control electrodes 176 and 178 may be fabricated on substrate 144, which may also include a central spacer 146. The height of spacer 146 may be controlled to nanometer precision through standard epitaxial

1 growth techniques, and the fiber-ring resonator may be bonded to or otherwise held in contact
2 with spacer 146 to achieve reliable, reproducible, and stable relative positioning of modulator
3 optical resonator 140 and WGM fiber-ring resonator 120.

4 In a second group of embodiments of the present invention, a level of optical power
5 transfer from the whispering-gallery optical mode to the modulator optical element 130 (through
6 evanescent optical coupling) is controlled by modulating the relative phase matching of the
7 whispering-gallery optical mode and a modulator optical mode in the interaction region thereof.
8 The modulator optical element 130 in these so-called "index-modulated" embodiments may
9 comprise an open optical waveguide structure (in which an optical mode of the waveguide does
10 not follow a closed path, re-circulate, or resonate within the waveguide; referred to hereinafter as
11 a "modulator waveguide"), or may comprise a ring, resonator, or other closed optical waveguide
12 structure (in which an optical mode of the waveguide may re-circulate and/or resonate; referred
13 to collectively hereinafter as a "modulator resonator"). These modulator elements may be either
14 low-finesse (less than about 10; less "resonator-like") or high-finesse (greater than about 10;
15 more "resonator-like"), depending on the particular device configuration employed. In either
16 case, the modulator optical element 130 is positioned so that an evanescent portion of the
17 whispering-gallery optical mode at least partially spatially overlaps a modulator optical mode
18 whose modal index may be controlled, thereby enabling control of optical power transfer via
19 evanescent optical coupling (by control of phase matching) between the WGM resonator 120 and
20 the modulator waveguide 130. This in turn controls the round trip optical loss experienced by
21 the whispering-gallery optical mode in the WGM resonator 120, thereby enabling the desired
22 goal of controlled modulation of transmission of the propagating optical mode through the
23 transmission waveguide 110.

24 In a third group of embodiments of the present invention, a modulator optical element
25 130 may comprise a modulator optical resonator for supporting a modulator optical mode whose
26 modal index may be controlled, thereby also shifting a resonance wavelength thereof. In such
27 "resonance-modulated" embodiments, optical power transfer (through evanescent optical
28 coupling) from the whispering-gallery optical mode to a modulator optical mode is controlled by
29 shifting the modulator optical mode into and/or out of resonance with the whispering-gallery
30 optical mode. This in turn controls the round trip optical loss experienced by the whispering-

gallery optical mode in the WGM resonator 120, thereby enabling the desired goal of controlled modulation of transmission of the propagating optical mode through the transmission waveguide 110.

In a fourth group of embodiments of the present invention, a modulator optical element 130 may comprise a modulator optical waveguide or resonator, evanescently optically coupled to the WGM optical resonator 120 at two separate points, for supporting a modulator optical mode whose modal index between the two points may be controlled. In such "interference-modulated" embodiments, net optical power transfer (through evanescent optical coupling) from the whispering-gallery optical mode to a modulator optical mode is controlled by controlling the relative phase of the modulator optical mode and the whispering-gallery optical mode at the second coupling region. This in turn controls the round trip optical loss experienced by the whispering-gallery optical mode in the WGM resonator 120, thereby enabling the desired goal of controlled modulation of transmission of the propagating optical mode through the transmission waveguide 110.

A property common to each of the second, third, and fourth groups of embodiments is control of the modal index of a modulator optical mode in response to an applied control signal. This may be preferably achieved by use of a modulator waveguide or resonator fabricated incorporating an electro-refractive material, an electro-optic material and/or a non-linear optical material, thereby enabling control of the modal index through application of an electronic and/or optical control signal.

Examples of suitable electro-optic materials (typically non-centrosymmetric) include, but are not limited to: semiconductor materials, including zincblende semiconductors; quantum well materials; multi-quantum well (MQW) materials, including materials exhibiting the quantum confined Stark effect (QCSE), Franz-Keldysh effect (FKE), quantum-confined Franz Keldysh effect (QCFKE), or similar mechanism; crystalline oxide electro-optic materials such as lithium niobate (LNB), potassium niobate (KNB), potassium dihydrogen phosphate (KDP), and so forth; organic and/or polymeric electro-optic materials, including poled chromophore-containing polymers; liquid crystals; hybrid layered materials comprising an electro-optic layer in contact with or incorporated within a Bragg multi-layer dielectric stack for supporting surface-guided optical modes (SGOMs) such as surface-guided Bloch modes (SGBMs), for example; hybrid

1 layered materials comprising an electro-optic layer in contact with, incorporated within, or
2 positioned between a pair of Bragg multi-layer dielectric stacks; combinations thereof; and/or
3 functional equivalents thereof. A modulator control element may comprise control electrodes
4 operatively coupled to the modulator optical element for enabling control of the modal index of
5 the modulator optical mode in the modulator optical element by application of an electronic
6 control voltage and/or current to the electro-optic or electro-refractive material. Optical
7 excitation of some of these materials may also serve to generate charge carriers, thereby enabling
8 control of the modal index by application of an optical control signal. Materials exhibiting non-
9 linear optical polarizability, saturable optical polarizability, non-linear Kerr effect, and/or other
10 non-linear optical responses may be incorporated into the modulator optical element to enable
11 control of the modal index thereof by application of an optical control signal.

12 Index-modulated embodiments of an optical power control device according to the
13 present invention are shown in Figs. 2A, 2B, 3A, and 3B in which the modulator optical element
14 comprises an open modulator optical waveguide positioned tangentially with respect to the
15 WGM optical resonator. Transmission waveguide 110 is shown as a fiber-optic taper. A fiber-
16 optic waveguide having a saddle-shaped evanescent coupling portion, as described in detail in
17 earlier-cited application A6, or other fiber-optic waveguide could be equivalently employed.
18 WGM optical resonator 120 is shown as a fiber-ring resonator as described in detail in earlier-
19 cited application A5. Other WGM resonator structures could be equivalently employed. In Figs.
20 2A and 2B, the modulator optical element is a slab waveguide 132 in substantial tangential
21 engagement with WGM resonator 120, either in direct mechanical contact, or positioned at a
22 specific distance from the WGM resonator to yield a desired level of evanescent optical
23 coupling.

24 An evanescent portion of the whispering-gallery optical mode supported by WGM
25 resonator 120 extends radially beyond the circumference thereof, and therefore spatially overlaps
26 a portion of the slab waveguide 132. Index-modulated slab waveguide 132 may preferably be
27 fabricated incorporating an electro-optic or electro-refractive material, so that the modal index
28 of a modulator optical mode may be controlled by a modulator control element. The electro-
29 optic material need only be present in the interaction region (i.e., the volume of overlap between
30 the evanescent portion of the whispering-gallery optical mode and the slab waveguide) which is

1 typically limited in spatial extent by the size and curvature of WGM resonator 120, although the
2 electro-optic material may also be present elsewhere in the waveguide. The modal index shift in
3 response to a control signal may preferably be sufficiently large to enable the WGM resonator
4 round trip optical loss (due to evanescent coupling into the modulator waveguide) to reach a
5 level comparable to the optical coupling between the transmission waveguide 110 and the
6 resonator 120 (i.e., to achieve critical coupling; typically loss on the order of about 0.5% to
7 about 5% per round trip is needed to yield linewidths consistent with typical WDM, TDM, or
8 other optical data transmission systems; typically on the order of 1-40 GHz), or alternatively, to
9 enable the WGM resonator round trip loss to exceed critical coupling. The slab waveguide
10 should be kept thin (comparable to the radial extent of the evanescent portion of the whispering-
11 gallery optical mode beyond the circumference of resonator 120) and the index of refraction of
12 any substantially homogeneous medium in contact with the face of the slab opposite the WGM
13 resonator (i.e., a substrate or cladding layer) must be less than the refractive index of the slab
14 waveguide and no greater than the refractive index of the WGM resonator. In this way optical
15 power is confined within waveguide 132 near resonator 110, thereby substantially eliminating
16 undesired optical loss. Otherwise optical power coupled from the WGM resonator 120 into slab
17 waveguide 132 could propagate away from resonator 110 and be lost.

18 Modal index mismatch (i.e., phase mismatch) between the whispering-gallery optical
19 mode and the slab waveguide must be carefully controlled so that, by switching the slab
20 waveguide modal index between two operational levels, the round trip optical loss of the WGM
21 optical resonator (due to coupling of optical power into the modulator waveguide and dissipation
22 therefrom) may be switched between under- and critically-coupled conditions, or between
23 critically- and over-coupled conditions. For example, the slab waveguide material might be
24 chosen to yield a relatively large phase mismatch, thereby limiting the transfer of optical power
25 to the slab (characteristic spatial period short compared to interacting propagation distance) and
26 resulting in over-coupling, while the application of a control signal may change the modal index
27 so as to reduce the phase mismatch (thereby lengthening the spatial period) and thereby increase
28 transfer of optical power to the slab to a sufficiently high level to result in critical-coupling and
29 near-zero transmission of the propagating optical mode through the transmission optical
30 waveguide. In a second example, the slab and WGM resonator might be well phase-matched

1 and the coupling chosen to yield a critical-coupling condition (interaction length about one-half
2 the characteristic spatial period), while the modal index of the slab may be switched to a level
3 that results in phase-mismatch (interaction length roughly equal to the characteristic spatial
4 period) and an over-coupled condition. Many other schemes and combinations of modal index
5 operational levels and phase match/mismatch between the WGM resonator and the slab
6 waveguide may be employed while remaining within the scope of inventive concepts disclosed
7 and/or claimed herein. For a given WGM optical resonator geometry, slab waveguide material,
8 and so forth, some experimentation is typically required to determine the level of evanescent
9 coupling, and the appropriate operational levels of slab waveguide modal index to produce the
10 desired modulation of the WGM resonator round trip loss.

11 Dissipation of optical power from the modulator waveguide may be achieved in a variety
12 of ways. The optical power may be allowed to simply propagate in the modulator waveguide
13 away from the interaction region to radiate into the environment, without an opportunity to
14 couple back into the WGM resonator. Alternatively, the modulator waveguide may be provided
15 with a region of high optical loss (which need not be modulated). The high-loss region may
16 encompass all or a portion of the modulator waveguide, and may or may not be spatially separate
17 from the interaction region. The optical loss may be provided in myriad functionally equivalent
18 ways, including but not limited to optical absorption and optical scattering, and optical power
19 coupled into the modulator waveguide from the WGM resonator may propagate in the region of
20 high optical loss and be absorbed or otherwise dissipated. Any functionally equivalent means for
21 dissipating optical power transferred into the modulator waveguide from the WGM optical
22 resonator may be employed without departing from inventive concepts disclosed and/or claimed
23 herein.

24 In Figs. 3A and 3B, the modulator optical element is an index-modulated two-
25 dimensional (2D) waveguide 134 on a substrate 136 and positioned tangentially with respect to
26 WGM optical resonator 120 (in this example a fiber-ring WGM resonator as described in earlier
27 cited application A5; other WGM structures may be equivalently employed). Most of the same
28 considerations applicable to the index-modulated slab waveguide embodiment of Figs. 2A and
29 2B apply to the 2D waveguide embodiment of Figs. 3A and 3B. The 2D waveguide 134 may
30 preferably be fabricated incorporating an electro-optic or electro-refractive material, so that the

1 modal index of a modulator optical mode may be controlled by a modulator control element, and
2 which may produce WGM resonator round trip loss sufficient to achieve critical coupling.
3 Modal index mismatch between the 2D waveguide and the WGM optical resonator must be
4 controlled in the manner described hereinabove for the index-modulated slab waveguide. In
5 addition to the 2D waveguide material and the substrate material, the transverse geometry of the
6 2D waveguide must also be chosen to yield the desired spatial overlap and phase
7 match/mismatch properties.

8 The modal index of index-modulated slab waveguide 132 or 2D waveguide 134 may be
9 controlled by electronic, optical, and/or other means. For example, a quantum well, multi-
10 quantum well (MQW), other semi-conductor, or any other suitable electro-optic material may be
11 incorporated into the modulator waveguide as an electro-optic material, so that the modal index
12 of the modulator waveguide may be altered by application of a control electric field. For
13 wavelengths between about 1.2 μm and 1.7 μm , the InGaAsP MQW material described in detail
14 hereinabove may be used as a suitable electro-optic material, with the modal index shifted by
15 application of a control electric field through QCSE, FKE, QCFKE, or other similar mechanism.
16 The properties of the MQW material must differ slightly depending on whether the material is to
17 be used as an electro-absorptive material or an electro-refractive material. In both cases the
18 bandgap of the barrier layers should preferably be substantially greater than the photon energy of
19 the light to be modulated. For an electro-absorptive material, however, the quantum well
20 bandgap should be between about 30 meV and about 60 meV above the photon energy (in
21 contrast to 10-30 meV for an electro-absorptive material), so that the modulator waveguide does
22 not introduce unwanted optical loss. A modulator control element may comprise control
23 electrodes suitably positioned to apply the control electric field. Alternatively, the modal index
24 of such materials may be controlled by injection of current into the material. The presence of
25 additional charge carriers (electrons or holes, as the case may be) may serve to increase or
26 decrease the modal index of the waveguide material, depending on the bandgap, band structure,
27 and/or doping of the semiconductor and the wavelength of the optical mode to be modulated.
28 Control electrodes or other electrical contact may serve to inject a control electrical current.
29 Optical excitation of such materials may also serve to generate charge carriers, thereby allowing
30 control of the waveguide modal index to be controlled by application of an optical control signal.

1 Other classes of materials exhibiting non-linear optical polarizability, saturable optical
2 polarizability, non-linear Kerr effect, and/or other non-linear optical responses may be
3 equivalently incorporated into the modulator waveguide to enable control of the waveguide
4 modal index by application of an optical control signal. As with the loss-modulated
5 embodiments, many other electro-optic materials or material combinations may be employed to
6 implement an index-modulated embodiment operable at other wavelengths. Several suitable
7 material combinations are disclosed in earlier-cited application A7.

8 An index-modulated embodiment of an optical power control device according to the
9 present invention is shown in Figs. 4A and 4B in which the modulator optical element comprises
10 an open arcuate modulator optical waveguide 138 positioned axially with respect to the WGM
11 optical resonator. Transmission waveguide 110 is shown as a fiber-optic taper. A fiber-optic
12 waveguide having a saddle-shaped evanescent coupling portion, as described in detail in earlier-
13 cited application A6, or other fiber-optic waveguide could be equivalently employed. WGM
14 optical resonator 120 is shown as a fiber-ring resonator as described in detail in earlier-cited
15 application A5. Other WGM resonator structures could be equivalently employed. In Fig. 4A
16 spacer 139 is shown for positioning arcuate waveguide 138 at the proper distance from WGM
17 resonator 120. In this particular embodiment the spacer 139 comprises a portion of an adjacent
18 fiber segment connected to the fiber-ring resonator with arcuate waveguide 138 deposited
19 thereon, bonded thereto, or otherwise held in contact therewith. Some experimentation will
20 typically be required to determine the spacing between WGM resonator 120 and arcuate
21 waveguide 138 that produces the desired level of round-trip optical loss for WGM resonator 120
22 and the appropriate phase matching conditions between WGM resonator 120 and arcuate
23 waveguide 138. Once the proper thickness of spacer 139 has been determined, it may be
24 reproducibly fabricated by cleaving, etching, machining, lithography, cylindrical lithography, or
25 other suitable processing of the adjacent fiber segment. A similar spacer may be employed for
26 other types of WGM resonator as well. The same types of materials used for the index-
27 modulated slab and 2D waveguides described hereinabove may be employed for fabricating
28 index-modulated arcuate waveguide 138. In particular, arcuate waveguide 138 may comprise the
29 InGaAsP multi-quantum well material described hereinabove, with the alternating quantum well
30 and barrier layers substantially parallel to WGM resonator 120 and with the control electric field

1 applied substantially perpendicular to WGM resonator 120. An advantage of this embodiment is
2 increased interaction length between the whispering-gallery optical mode and the arcuate
3 waveguide relative to the tangentially positioned waveguides, therefore requiring smaller modal
4 index shifts to achieve the same changes in power transfer through evanescent optical coupling
5 to and round trip optical loss from the WGM resonator.

6 A significant property of both tangentially- and axially-positioned index-modulated open
7 modulator optical waveguide structures is that since no re-circulation of any waveguide optical
8 mode occurs, the presence of the modulator optical waveguide has a substantially negligible
9 effect on the wavelength-dependent properties and/or resonant behavior of the adjacent WGM
10 optical resonator. Such wavelength/frequency shifting behavior can adversely affect the
11 performance of an optical power control device according to the present invention, or
12 alternatively may be exploited to enhance said performance, depending on the design,
13 construction, and use of a particular device.

14 Various index-modulated embodiments of an optical power control device according to
15 the present invention are shown schematically in Figs. 5A through 5E in which the modulator
16 optical element comprises a closed optical waveguide (i.e., a modulator optical resonator 140)
17 positioned tangentially (Figs. 5A and 5B) or axially (Figs. 5C, 5D, and 5E) with respect to the
18 WGM resonator 120, and oriented substantially parallel to (Figs. 5A, 5C, and 5D) or
19 substantially perpendicular to (Figs. 5B and 5E) the WGM resonator 120. Transmission
20 waveguide 110 is shown as a tapered fiber-optic waveguide. A fiber-optic waveguide having a
21 saddle-shaped evanescent coupling portion, as described in detail in earlier-cited application A6,
22 or other fiber-optic waveguide could be equivalently employed. WGM optical resonator is
23 shown as a micro-disk or micro-ring resonator. Other WGM resonator structures could be
24 equivalently employed. Index-modulated modulator optical resonator 140 may comprise any of
25 the resonator structures recited earlier for WGM resonator 120, including but not limited to
26 spheres, near-spheres, oblate and/or prolate spheroids, ovals, ovoids, racetracks, ellipsoids,
27 polygons, polyhedra, cylinders, disks, rings, micro-spheres, micro-disks, micro-rings, fiber-rings,
28 disks and/or rings on substrates (including structures disclosed in earlier-cited application A7),
29 ring or other closed waveguides, and/or functional equivalents thereof, and are shown generically
30 as micro-disks or micro-rings in Figs. 5A through 5E. Index-modulated modulator optical

1 resonator 140 is shown in Figs. 5A and 5B in substantial tangential engagement with WGM
2 optical resonator 120, either in direct mechanical contact, or positioned at a specific distance
3 from the WGM resonator (by a spacer or other suitable alignment structure) to yield a desired
4 level of evanescent optical coupling. An evanescent portion of the whispering-gallery optical
5 mode extending radially beyond WGM resonator 120 may overlap a portion of modulator optical
6 resonator 140, either a radially-extending portion thereof when substantially parallel to WGM
7 resonator 120 (Fig. 5A), or an axially-extending portion thereof when substantially perpendicular
8 to WGM resonator 120 (Fig. 5B). Index-modulated modulator optical resonator 140 is shown in
9 Figs. 5C, 5D, and 5E positioned axially with respect to WGM optical resonator 120, either in
10 direct mechanical contact, or positioned at a specific distance from the WGM resonator (by a
11 spacer or other suitable alignment structure) to yield a desired level of evanescent optical
12 coupling. An evanescent portion of the whispering-gallery optical mode extending axially
13 beyond WGM resonator 120 may overlap a portion of modulator optical resonator 140, either an
14 axially-extending portion thereof when substantially parallel to WGM resonator 120 (Figs. 5C
15 and 5D), or a radially-extending portion thereof when substantially perpendicular to WGM
16 resonator 120 (Fig. 5E).

17 Index-modulated modulator optical resonator 140 may preferably be fabricated
18 incorporating an electro-optic material, so that the modal index of a modulator resonator optical
19 mode may be controlled by a modulator control element. The modulator optical resonator 140
20 should preferably have a resonant optical mode having substantially the same wavelength as the
21 whispering-gallery optical mode of WGM resonator 120 (and hence the propagating optical
22 mode to be controlled). This enables transfer of optical power from the WGM resonator and
23 build-up of optical power within the modulator optical resonator, in turn enabling dissipation of
24 optical power from modulator resonator 140 to produce sufficiently large round trip optical loss
25 for the WGM resonator 120 coupled thereto. If the modulator optical resonator and WGM
26 optical resonator are not resonant with each other, in contrast, the modulator resonator would
27 have a negligible effect on the round-trip loss of the WGM resonator. Index-modulated
28 modulator optical resonator 140 may preferably be fabricated incorporating an electro-optic
29 material, so that the modal index of a modulator resonator optical mode may be controlled by a
30 modulator control element. A complication encountered when implementing an embodiment

1 that includes an index-modulated modulator resonator arises from the unavoidable wavelength
2 shift of the resonant optical mode of the modulator resonator that occurs with a change in the
3 modal index thereof. The WGM resonator and modulator optical resonator must be treated as a
4 coupled-cavity system, and shifts in the modulator resonance wavelength may perturb the
5 resonances of the coupled system. This effect must be properly accounted for in designing an
6 optical power control device incorporating a modulator optical resonator, or alternatively, the
7 effect may be exploited for designing optical power control devices with specific wavelength
8 dependent performance characteristics. One approach might involve providing the modulator
9 resonator with two index-modulated regions: one at the interaction region near the WGM
10 resonator and another far from the WGM resonator. Application of a control signal may serve to
11 change the modal index in the interaction region to change the level of optical power transfer by
12 evanescent optical coupling, while the modal index in the second region may change by an
13 appropriate amount to leave the resonance frequency of the modulator resonator substantially
14 unchanged. The effects of shifting resonances in the coupled-cavity system may be somewhat
15 mitigated for a low-Q index-modulated resonator modulator element, since the dissipation of
16 optical power from the modulator resonator tends increase the bandwidth of its resonances, in
17 turn decreasing the effect of the modulator resonances on the WGM resonances in the coupled-
18 cavity system. In short, index- or coupling-modulated resonators or "closed waveguide"
19 modulator optical elements having relatively low finesse (less than about 10) may behave
20 substantially less "resonator-like" than the relatively high-finesse WGM resonator.

21 Alternatively, the modulator optical resonator 140 may be a relatively high-Q resonator
22 and should preferably have a resonant optical mode having substantially the same wavelength as
23 the whispering-gallery optical mode of WGM resonator 120 (and hence the propagating optical
24 mode to be controlled). Transfer of optical power from the whispering-gallery optical mode of
25 WGM resonator 120 into modulator optical resonator 140, and subsequent dissipation of optical
26 power therefrom, may be modulated (to a degree sufficient to switch the optical power control
27 device between conditions of under- and critical-coupling, or between conditions of critical- and
28 over-coupling) by modulation of the modal index of the modulator resonator 140 to shift the
29 resonance wavelength thereof from a condition of resonance with the whispering-gallery optical
30 mode (yielding greater optical power transfer to the modulator optical mode) to a condition of

1 non-resonance with the whispering-gallery optical mode (yielding little or no optical power
2 transfer to the modulator optical mode). Dissipation of optical power from the modulator
3 resonator 140 in such a “resonance-modulated” device may be achieved in a variety of ways.
4 The dissipated optical power may be allowed to simply propagate in the modulator resonator
5 away from the interaction region to radiate into the environment, without an opportunity to
6 couple back into the WGM resonator. Alternatively, the modulator resonator may be provided
7 with a region of high optical loss (which need not be modulated). The high-loss region may
8 encompass all or a portion of the modulator resonator, and may or may not be spatially separate
9 from the interaction region. The optical loss may be provided in myriad functionally equivalent
10 ways, including but not limited to optical absorption and optical scattering, and optical power
11 coupled into the modulator resonator from the WGM resonator may propagate in the region of
12 high optical loss and be absorbed or otherwise dissipated. Any functionally equivalent means for
13 dissipating optical power transferred into the modulator resonator from the WGM optical
14 resonator may be employed without departing from inventive concepts disclosed and/or claimed
15 herein.

16 Any of the electro-optic materials recited hereinabove for an index-modulated modulator
17 waveguide, or functional equivalents thereof, may be incorporated into a modulator resonator
18 according to the present invention, with suitable adjustment to yield electro-refractive behavior
19 instead of electro-absorptive behavior. An index- or resonance-modulated modulator optical
20 resonator may be positioned relative to a WGM fiber-ring resonator by a spacer as shown in
21 Figs. 6A-6C, Fig. 7, and Figs. 8A-8B.

22 A preferred material for any of the index-modulated modulator optical waveguides and/or
23 resonators of Figs. 3A-3B, 4A-4B, 5B-5D, 6A-6B, and/or Fig. 7 may be a Bragg multi-layer
24 dielectric stack (also referred to as a distributed Bragg reflector, or DBR, stack). Such multi-
25 layer DBR stacks support and/or guide propagation of so-called surface guided optical modes
26 (SGOMs) such as surface-guided Bloch modes (SGBMs), for example. A SGOM supported by
27 any of the index-modulated modulator waveguides and/or modulator resonators of Figs. 3A-3B,
28 4A-4B, 5B-5D, 6A-6B, and/or Fig. 7 (fabricated as a DBR stack) may serve as the modulator
29 optical mode. The surface-guided modulator optical mode may be evanescently optically
30 coupled to the whispering-gallery optical mode from the top of the Bragg stack (referred to as

1 “surface-coupled”), or from the side of the Bragg stack (referred to a “side-coupled”). The
2 Bragg stack is preferably fabricated (typically using epitaxial, evaporative, effusive, and/or
3 chemical vapor deposition/growth techniques, wafer-bonding techniques, and/or other related
4 techniques) incorporating an electro-optic layer and control electrodes for applying a control
5 electric field to control the material index of the electro-optic layer. The strongly dispersive
6 optical properties of a DBR-guided SGOM (a substantially flat dispersion relation in the
7 operating wavelength range, so that a narrow range of wavelengths cover a wide range of
8 propagation constants or modal indices) serve to produce a substantially larger modal index shift
9 of the SGOM for a given applied control voltage level than previous electro-optic devices. This
10 in turn enables optical power control devices incorporating electro-optic/DBR waveguides or
11 resonators according to the present invention to be operated with substantially smaller control
12 voltages (and lower electrical drive power consumption) than their counterparts incorporating
13 simpler electro-optic materials and/or geometries. A wide variety of material combinations,
14 layer sequences, and/or fabrication/processing techniques may be employed to implement an
15 electro-optic/DBR stack embodiment of the present invention. Many examples of such surface-
16 guiding electro-optic/DBR stack waveguides and/or resonators are disclosed in earlier-cited
17 application A7, and any of those examples may be employed in an index-modulated, surface-
18 coupled modulator, and/or a resonance-modulated, surface-coupled modulator resonator, without
19 departing from inventive concepts disclosed and/or claimed herein.

20 In an alternative embodiment of any of the index-modulated modulator optical
21 waveguides and/or resonators of Figs. 3A-3B, 5A, and/or 5E, a pair of DBR stacks may be
22 employed surrounding a core layer. In such structures the modulator optical mode may be
23 supported and substantially confined by the Bragg stacks in a region near the core layer. The
24 confined modulator optical mode may be evanescently optically coupled to the whispering-
25 gallery optical mode from the side of the Bragg stack (“side-coupled”). The Bragg stack is
26 preferably fabricated (typically using epitaxial, evaporative, effusive, and/or chemical vapor
27 deposition/growth techniques, wafer-bonding techniques, and/or other related techniques)
28 incorporating an electro-optic layer and control electrodes for applying a control electric field to
29 control the material index of the electro-optic layer. The strongly dispersive optical properties of
30 a dual-DBR-guided confined optical mode enable operation of devices with substantially smaller

1 control voltages (and lower electrical drive power consumption) than their counterparts
2 incorporating simpler electro-optic materials and/or geometries, in a manner analogous to that
3 described hereinabove for SGOMs. Many examples of such electro-optic/dual-DBR stack
4 waveguides and/or resonators are disclosed in earlier-cited application A7, and any of those
5 examples may be employed in an index-modulated, side-coupled modulator, and/or a resonance-
6 modulated, side-coupled modulator resonator, without departing from inventive concepts
7 disclosed and/or claimed herein.

8 Exemplary fabrication procedures and cross-sectional structures of index-modulated
9 electro-optic/Bragg stack waveguides or resonators are depicted in Figs. 9 through 16. The
10 flowchart of Fig. 9 and process diagram of Fig. 10 illustrate fabrication (by epitaxial techniques
11 and/or other functionally equivalent deposition/growth/processing techniques) of a Bragg multi-
12 layer dielectric stack 2202 and a high-index core layer 2204 on a first substrate 2210, the Bragg
13 stack comprising alternating $\lambda/4$ (quarter-wave) layers of materials differing in material
14 refractive index. A preferred Bragg stack may comprise alternating $\lambda/4$ layers of GaAs (index
15 about 3.5) and high-aluminum-fraction AlGaAs (between about 0.90 and about 0.97 aluminum;
16 index about 3.2) on a GaAs substrate. In general the appropriate quarter-wave thickness is
17 determined based on the index of the material ultimately present in a given layer; this may not be
18 the same material initially deposited if subsequent processing (oxidation, for example) brings
19 about a chemical conversion of the layer to a new material. A doped layer 2220 of InGaAs may
20 be provided between the substrate 2210 and the Bragg stack 2202 to enable subsequent electrical
21 contact for applying the control voltage, and a GaAs or AlGaAs cladding layer may be provided
22 on top of the Bragg stack if desired.

23 On a second substrate 2240, a MQW material electro-optic layer 2208 may be fabricated
24 (for example, the InGaAsP MQW material as described hereinabove for use as an electro-
25 absorptive or electro-optic material for wavelengths from about 1.2 μm to about 1.7 μm ; other
26 functionally equivalent electro-optic materials may be used) and may include cladding layers
27 above and below the MQW layers (if desired) and a doped layer 2230 between the MQW layer
28 2208 and the substrate 2240 to enable subsequent electrical contact for applying the control
29 voltage. The top of the MQW material 2208 (or the top cladding layer, if present) is then wafer-
30 bonded or equivalently secured to the high-index core layer 2204 (or top cladding layer, if

present) on the Bragg stack 2202. The MQW substrate 2240 may then be etched away or otherwise equivalently removed, leaving the MQW electro-optic layer 2208, contact layer 2230, and bottom cladding layer (if present) exposed and accessible for subsequent evanescent optical surface coupling to the WGM optical resonator. Use of wafer-bonding techniques in this example is required due to the lattice mismatch between the GaAs/AlGaAs DBR stack and the InGaAsP MQW. If lattice-compatible materials are employed for the DBR and the electro-optic layer, then both may be deposited sequentially on a single substrate, and no wafer-bonding step is required. Numerous examples of DBR and electro-optic material combinations, some requiring wafer-bonding and others fabricated on a single substrate, are disclosed in earlier-cited application A7.

The wafer-bonded Bragg stack/MQW composite structure 2250 is then spatially-selectively etched (using etch mask 2270, for example) and/or otherwise processed to leave a protruding ridge structure of the appropriate shape (a straight or arcuate segment 2252 for an open waveguide as in Fig. 11; a ring, racetrack, or other closed path for a closed waveguide or resonator 2254 as in Fig. 12) on substrate 2210. As shown in cross-section in Figs. 13 and 14, ridge structure 4300 may be oxidized, converting lateral portions 4332 of each AlGaAs layer 4330 to aluminum oxide and leaving a central portion 4334 of AlGaAs in each of the AlGaAs layers 4330. These central AlGaAs portions 4334 together with GaAs layers 4320 form a core of the waveguide (or resonator) structure 4300, while the lateral aluminum oxide portions 4332 together form lateral cladding layers of the waveguide (or resonator) structure 4300. The aluminum fraction of each of the AlGaAs layers may be the same, yielding a waveguide (or resonator) core of substantially uniform width upon lateral oxidation (Fig. 13), or the aluminum fraction may decrease from the bottom of the Bragg stack near the substrate up towards the top of the stack, yielding a waveguide (or resonator) core that is narrower at the bottom of the Bragg stack near the substrate and that becomes wider toward the top of the stack upon lateral oxidation (Fig. 14). Oxidation proceeds more rapidly with increasing Al content of a given layer.

The MQW material acts as an electro-optic spacer on the Bragg stack waveguide (or resonator), and application of the control voltage across the doped contact layers changes the material index of the MQW. This in turn results in substantially larger changes in the modal index of the SGOM supported by the Bragg stack, and therefore substantial shifts in the phase

1 matching condition (and degree of optical power transfer between under-, critical-, and/or over-
2 coupling) between the Bragg stack and the WGM resonator. Larger changes in the level of
3 optical power transfer may be achieved for a given applied control voltage using an electro-
4 optic/Bragg stack device than by using a simple electro-optic device as described earlier herein,
5 enabling substantial reduction of control voltage and electrical drive power to operate an optical
6 power control device. While Bragg multi-layer dielectric stacks fabricated from GaAs/AlGaAs
7 are currently preferred (since they are already well-understood and well-characterized and yield
8 high-index-contrast DBR structures), other combinations of materials yielding functionally
9 equivalent Bragg stacks (currently known or hereafter developed) may be employed without
10 departing from inventive concepts disclosed and/or claimed herein. Similarly, while InGaAsP
11 multi-quantum well materials are currently preferred (since they are already well-understood and
12 well-characterized, and are suitable for use in the technologically important 1.2-1.7 μm
13 wavelength range), other multi-quantum well materials yielding functionally equivalent electro-
14 optic properties (currently known or hereafter developed) may be employed without departing
15 from inventive concepts disclosed and/or claimed herein. Alternatively, any of the electro-optic
16 materials disclosed hereinabove may be equivalently employed for fabricating an electro-optic
17 spacer in conjunction with a Bragg stack as disclosed herein.

18 The flowchart of Fig. 15 and the fabrication process diagram of Fig. 16 illustrate
19 fabrication (by epitaxial and/or other functionally equivalent growth/deposition/processing
20 techniques) of a Bragg multi-layer dielectric stack 2002 and high-index core layer 2004 on a
21 substrate 2010. At least one layer of the Bragg stack 2002 is an electro-optic material layer. An
22 exemplary Bragg stack of this type may comprise alternating $\lambda/4$ layers of high-aluminum-
23 fraction AlGaAs and GaAs/InGaAs MQW material on a GaAs substrate, and may include top
24 and bottom doped InGaAs contact layers 2020 and 2030 and a top GaAs cladding layer. The
25 Bragg stack 2002 is processed (by lithography or other functionally equivalent technique) to
26 form a ridge structure and laterally oxidized as described hereinabove, yielding a central core
27 and lateral cladding for the waveguide (or resonator) structure, which may be evanescently
28 optically surface-coupled to the WGM optical resonator. Application of a control voltage across
29 the contact layers 2020 and 2030 results in a shift of the material index of the GaAs/InGaAs
30 MQW material, substantially larger shifts in the modal index of the SGOM, and substantial shifts

1 in the phase matching condition (and degree of optical power transfer between under-, critical-,
2 and/or over-coupling) between the Bragg stack waveguide and the WGM resonator.
3 GaAs/InGaAs MQW material is not ideally suited for modulating optical wavelengths typically
4 used in long-haul fiber-optic telecommunications (between about 1.2 mm and about 1.7 mm), but
5 rather better suited for the 0.7-0.8 μm region (often utilized for so-called metro, or short-haul
6 fiber-optic telecommunications networks). Bragg stacks incorporating any suitable MQW
7 materials or other electro-optic materials (including InGaAsP MQW material, suitable for typical
8 fiber-optic telecommunications wavelengths), currently known or hereafter developed, may be
9 equivalently employed without departing from inventive concepts disclosed and/or claimed
10 herein. Suitable combinations of materials will typically be determined by lattice-compatibility,
11 bandgap, operating wavelength, and so on.

12 Any of the electro-optic/Bragg stack structures described hereinabove and/or disclosed in
13 earlier-cited application A7 may be used to fabricated a resonance-modulated modulator optical
14 resonator, wherein the modal index shift of the applied control voltage functions to shift the
15 resonance wavelength of the modulator optical mode (SGOM in this case) into and out of
16 resonance with the whispering-gallery optical mode. The shifting of the resonance wavelength
17 of the modulator resonator serves to switch the level of optical power transfer from the WGM
18 resonator between under-, critical-, and/or over-coupling, as described hereinabove.

19 As a further generalization of resonant optical power control devices according to the
20 present invention, the WGM resonator may comprise a Bragg stack structure fabricated in a
21 manner analogous to the fabrication procedures described herein and in earlier-cited application
22 A7. Such a WGM optical resonator may comprise a single Bragg stack structure supporting a
23 surface-guided resonant optical mode, and evanescent optical coupling between the WGM
24 resonator and the transmission waveguide and between the WGM resonator and the modulator
25 optical element may occur through an axially-extending evanescent portion of the surface-guided
26 optical mode of the WGM resonator. Alternatively, the WGM optical resonator may comprise a
27 dual Bragg stack structure substantially confining a resonant optical mode therebetween, and
28 evanescent optical coupling between the WGM resonator and the transmission waveguide and
29 between the WGM resonator and the modulator optical element may occur through a radially-
30 extending evanescent portion of the confined optical mode of the WGM resonator.

1 In order to achieve and maintain reliable, reproducible, and stable evanescent optical
2 coupling between a transmission optical waveguide, a WGM resonator, and a modulator optical
3 element during and after manufacture of a resonant optical power control device according to the
4 present invention, an alignment device may be employed, as illustrated by the exemplary
5 assemblies of Figs. 17A-17C, 18A-18C, 19A-19B, 20A-20B, 21A-21B, 22A-22B, 23A-23B, and
6 24A-24B. Such an alignment device may comprise a first alignment substrate 502 having a
7 transmission-waveguide-alignment groove 506 thereon, and various embodiments are described
8 in detail in earlier-cited applications A4 and A5. Alignment substrate 502 may be further
9 provided with a WGM-resonator-alignment groove 504, or groove 504 may be provided on a
10 second alignment substrate 702. A method for fabricating a resonant optical power control
11 device according to the present invention comprises the steps of: 1) positioning and securing a
12 transmission fiber-optic waveguide within the transmission-waveguide-alignment groove 506;
13 and 2) positioning and securing the WGM optical resonator within the resonator-alignment
14 groove 504 (as shown, for example, in Figs 17A-17C and 18A-18C for the case when grooves
15 504 and 506 are both provided on substrate 502). The transmission fiber-optic waveguide may
16 comprise a fiber taper 600, an optical fiber 300 with a saddle-shaped evanescent optical coupling
17 segment, or any other functionally equivalent transmission optical waveguide having an
18 evanescent coupling segment. The WGM resonator may comprise a microsphere 620 connected
19 to a neck portion 622 of a microsphere fiber segment 624, a fiber-ring 602 connected to adjacent
20 fiber segments 604, or any other functionally equivalent WGM resonator structure.
21 Notwithstanding the exemplary combinations shown in the Figures, any suitable WGM resonator
22 may be combined with any suitable transmission fiber-optic waveguide to yield a resonant
23 optical power control device according to the present invention. The transmission-waveguide-
24 alignment groove 506 may be positioned on the alignment substrate 502, and resonator-
25 alignment groove 504 may be positioned on the alignment substrate 502 or 702, so that when
26 positioned and secured therein (and substrates 502 and 702 are assembled, if groove 504 is
27 provided on substrate 702), the transmission fiber-optic waveguide and the WGM resonator are
28 in substantial tangential engagement (usually mechanical contact between the waveguide and the
29 circumference of the resonator), thereby evanescently optically coupling the WGM resonator to
30 the transmission fiber-optic waveguide. Optical coupling between the WGM resonator and the

1 transmission fiber-optic waveguide may be achieved as long as at least portion of an evanescent
2 portion of one of the whispering-gallery optical mode of the resonator and a propagating optical
3 mode of the transmission fiber-optic waveguide spatially overlaps at least a portion of the other
4 optical mode. Actual mechanical contact is not required, only that the resonator and fiber be
5 sufficiently close to permit the overlap. However, in a preferred embodiment of an optical
6 power control device according to the present invention, optical coupling between the resonator
7 and the fiber may be most reproducibly, reliably, and stably achieved by positioning and
8 securing the WGM resonator and the transmission fiber-optic waveguide in mechanical contact
9 with one another.

10 The second alignment substrate 702 of the alignment device may also have the modulator
11 optical element secured thereto or mounted thereon. Alignment substrate 702 (and/or alignment
12 substrate 502, if groove 504 is provided thereon) may be suitably mechanically indexed or
13 otherwise provided with means for reliably, reproducibly, and stably positioning the modulator
14 optical element for evanescent optical coupling to the WGM optical resonator (either in direct
15 mechanical contact or a space therebetween). The alignment grooves 504 and 506, and any
16 indexing or other alignment means, together serve to suitably position the modulator optical
17 element, WGM resonator, and transmission fiber-optic waveguide relative to each other, when
18 all are secured to the assembled alignment device.

19 Similar alignment structures may be employed whether the modulator optical element is a
20 waveguide or resonator, and whether the modulator optical element is loss-modulated, index-
21 modulated, resonance-modulated, or interference-modulated. Exemplary assemblies include:
22 slab modulator waveguide 132 shown in Figs. 19A-19B (with groove 504 on substrate 502); 2D
23 modulator waveguide 134 on substrate 136 shown in Figs. 20A-20B (with groove 504 on
24 substrate 502); modulator resonator 140 (side-coupled, as in Fig. 5A) shown in Figs. 21A-21B
25 (with groove 504 on substrate 502); ridge modulator waveguide 2252 (surface-coupled) shown in
26 Figs. 22A-22B (with groove 504 on substrate 702); ridge modulator waveguide 2252 (side-
27 coupled) shown in Figs. 23A-23B (with groove 504 on substrate 702); and ridge modulator
28 resonator 2254 (surface-coupled, as in Fig. 5B) shown in Figs. 24A-24B (with groove 504 on
29 substrate 702). The embodiment of Figs. 24A-24B may be modified to provide side-coupling
30 between modulator resonator 2254 and fiber-ring resonator 602 (as in Fig. 5E).

1 The present invention has been set forth in the forms of its preferred and alternative
2 embodiments. It is nevertheless intended that modifications to the disclosed modulators for
3 optical power control devices, and methods of fabrication and use thereof, may be made without
4 departing from inventive concepts disclosed and/or claimed herein.